APPLIED PHYSICS LETTERS **97**, 134106 (2010)

All-angle blockage of sound by an acoustic double-fishnet metamaterial

J. Christensen,[1,a)] L. Martín-Moreno,[2] and F. J. García-Vidal[1,b)]
[1]*Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[2]*Departamento de Física de la Materia Condensada, Instituto de Ciencia de Materiales de Aragón (ICMA), CSIC–Universidad de Zaragoza, E-50009 Zaragoza, Spain*

(Received 28 June 2010; accepted 25 August 2010; published online 1 October 2010)

In this paper we design an acoustic metamaterial for broadband sound blockage that is easy to fabricate and presents tunable capabilities. Two adjacent holey plates are predicted to support a gap mode which is responsible of a forbidden band, displaying a negative effective bulk modulus. This acoustic metamaterial exhibits a weak dispersion with parallel momentum implying that strong attenuation appears for a broad range of angles of incident sound. Its bandwidth can be tailored at will by varying the separation between the two holey plates. [doi:10.1063/1.3491289]

Innovative periodic structures and composites have been recently developed in order to engineer sound propagation, aiming for selective acoustic blockage. Sound attenuation in phononic crystals[1–3] is based on the existence of forbidden bands whose origin mainly relies on diffraction by the periodic lattice. Another strategy is the use of sonic metamaterials in which a negative *effective* density, ρ, or a negative *effective* bulk modulus, $1/\kappa$, also leads to sound blockage. For example, locally resonant sonic metamaterials made of arrays of spheres posses a band of negative ρ,[4,5] whereas tubes with periodically distributed side branches are suitable to tune the effective $1/\kappa$ to negative values.[6,7] More recently, a one-dimensional composite medium with simultaneously negative ρ and $1/\kappa$ has been reported.[8] On the other hand, extensive work on electromagnetic (EM) metamaterials in the search for negative-index EM media[9,10] has inspired the design of acoustic metamaterials. One of the most efficient architectures presenting an effective negative EM refractive index is the so-called double-fishnet (DF),[11–14] whose basic structure consists of two holey metal films separated by a thin dielectric slab.

In this paper we analyze the scattering properties and the effective response of an acoustic DF (ADF) structure, i.e., two holey plates separated by a thin layer (see Fig. 1). We will show how the physics of this sonic metamaterial is quite different to that of its EM counterpart. Single holey plates have been recently examined, mainly in connection with the emergence of the phenomenon of extraordinary wave transmission through subwavelength apertures in acoustic systems.[15–19] Two resonant transmission mechanisms coexist in these structures. One is associated with the excitation of Fabry–Perot (FP) modes inside the holes, whereas the other mechanism relies on the coupling between the incident sound wave and acoustic surface waves confined at the horizontal surfaces of the holey plate.[18] A sketch of an ADF structure is depicted in Fig. 1. Two plates of thickness h_m are perforated with a square array (period Λ) of square holes of side a. These two holey plates are separated by a thin layer of thickness h_g, filled with a material characterized by a sound velocity c_g and mass density ρ_g. Similar results are obtained for other hole shapes and also for other types of periodic lattices. In our calculations we assume that the surrounding medium is air (sound velocity, c_0) and that the plates are made of steel or brass, in which the perfect rigid body approximation is very accurate. Within this approach, the same scattering properties are obtained in different frequency regimes by scaling all the geometrical parameters with the same factor. In our calculations, we will use Λ as the unit length defining the structure.

The theoretical formalism used throughout this work is based on the modal expansion of the pressure and velocity fields in the five regions forming the ADF structure (see Fig. 1). A detailed account of this general framework can be found in Ref. 18. In regions I, III, and V, the pressure is expanded in terms of plane waves whereas inside the holes (regions II and IV) the field is written as a linear combination of the corresponding waveguide eigenmodes. In Fig. 2 we render the normally-incident transmittance spectra for three different values of the gap thickness, $h_g=\Lambda/1000$, $\Lambda/100$, and $\Lambda/10$. The side of the square holes is fixed at $a=\Lambda/3.75$ and the gap material is assumed to be air. In the three panels, the dependence of the transmittance with wavelength, λ, and plates' thickness, h_m, is displayed. In the case of an extremely thin gap layer [Fig. 2(a)], transmission spectra are similar to those of single holey plates of total thickness $2h_m$. In this case, FP resonant modes appear at wavelengths close to $\lambda=4h_m/n$, with n an integer. Beyond these transmission peaks, in the ADF structure an additional resonant feature emerges, leading to a transmission dip at around

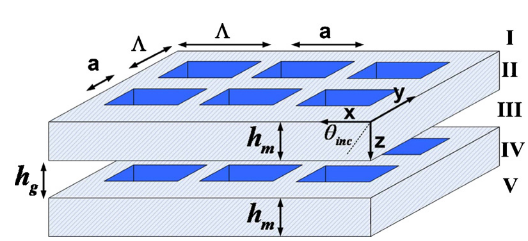

FIG. 1. (Color online) Schematic of an ADF metamaterial. The metal plates of thickness h_m and gap separation h_g are perforated with square holes of side a in a square lattice of period Λ. θ_{inc} defines the angle of incidence with respect to the normal.

[a)]Current address: Intituto de Optica-CSIC Serrano 121, 28006 Madrid, Spain.
[b)]Electronic mail: fj.garcia@uam.es.

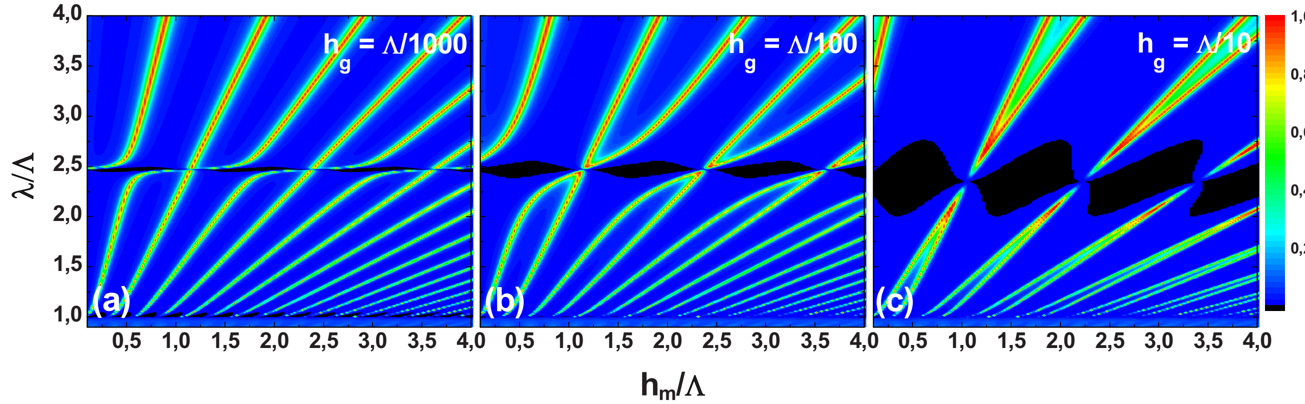

FIG. 2. (Color online) Normalized-to-unit cell transmittance spectra as a function of λ and h_m, both in units of Λ. In the three panels, $a=\Lambda/3.75$ and three different values of h_g are studied: $h_g=\Lambda/1000$, $\Lambda/100$, and $\Lambda/10$. The incident sound plane wave is impinging at the normal direction.

$\lambda=2.45\Lambda$. An inspection of the pressure field distribution associated with this resonance reveals that this mode is strongly localized at the gap region. Importantly, this gap mode seems to couple only with the odd FP-modes ($n=1,3,5\ldots$). When h_g is increased, the coupling between the odd FP-modes and the gap mode is enlarged and the spectral locations of these hybridized modes tend to merge with those of the even FP-modes, which remain almost unaltered as a function of h_g.

It is worth analyzing the scattering of sound waves by an ADF structure within the effective medium approach. For that, we extract the effective bulk modulus $1/\kappa$ and effective density ρ following the prescription described in Ref. 20. In order to analyze the link between transmission resonances and the effective $1/\kappa$, we have fixed the thickness of the plates at $h_m=\Lambda/1.875$. In this case, the spectral location of the gap mode lies exactly within the $n=1$ odd FP-resonance [see Fig. 2(a)]. As in Fig. 2, three different values of h_g are studied and rendered in Fig. 3: $h_g=\Lambda/1000$, $\Lambda/100$, and $\Lambda/10$. In all cases we find that the effective ρ is positive. This can be ascribed to the lack of cutoff for sound propagation inside the holes, whereas the existence of a cutoff for EM waves leads to a Drude behavior for the electric permittivity.[21] In the ADF structure, for a very thin gap layer, a region of negative $1/\kappa$ emerges and its location coincides with the transmission dip originated by the coupling between the gap mode and the first odd FP-mode. The consequence of a negative compressibility in the fluid element comprised by the unit cell (hole perforation plus gap), is the overall expansion as a reaction to a positive external pressure. As shown in Fig. 4(a), the width of the forbidden band, Δ in wavelength units, is greatly enlarged for increasing h_g as a result of a stronger coupling between the two modes. Therefore, our results suggest that in an ADF metamaterial the spectral linewidth of the attenuation band can be easily tuned by varying the separation between the two holey plates. When thinking in possible applications of ADFs for sound blockage, it is important to study the dispersion of its attenuation band with the angle of incidence. Moreover, this type of analysis is mandatory for analyzing the validity of the effective medium approach previously derived. In Fig. 4(b) we plot the evolution of the spectral locations of the resonant modes of the whole structure, along with the region of negative $1/\kappa$, as a function of the angle of incidence for the case depicted in Fig. 3(c) ($h_m=\Lambda/1.875$ and $h_g=\Lambda/10$). We classify the modes by their symmetry along the z-axis with respect to the middle xy-plane. As a difference with its optical counterpart,[21] all resonant modes and, consequently, the region of negative bulk modulus shows very little dispersion with parallel momentum. As shown in Fig. 4(b), the region of negative $1/\kappa$ is maintained for angles of incidence as large as 80°, although its bandwidth is reduced with respect to the normal incidence case. This weak dispersion fully validates

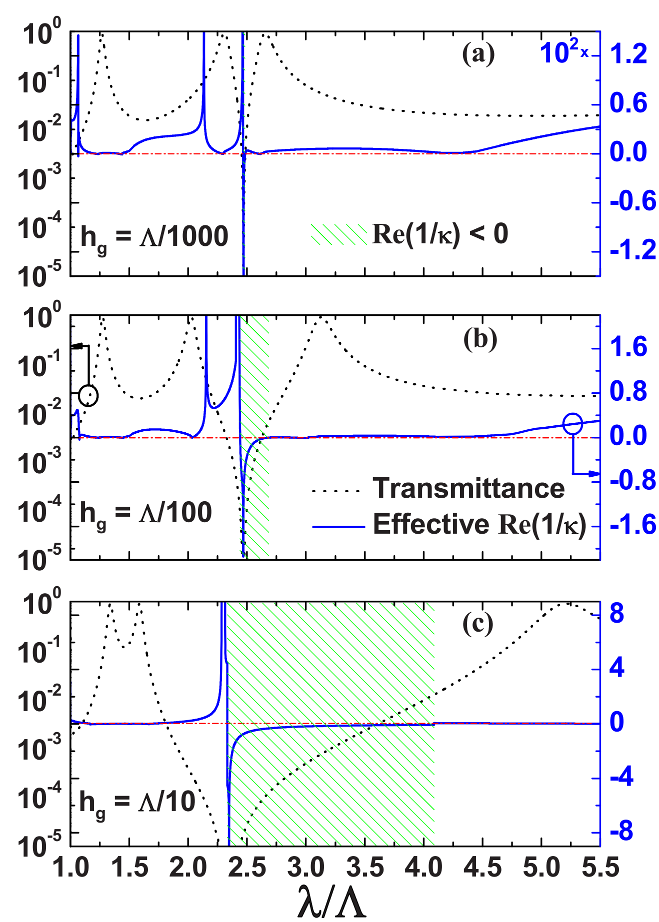

FIG. 3. (Color online) Normalized-to-unit-cell transmittance for normal incidence in logarithmic scale and the real part of the effective bulk modulus, $\mathrm{Re}(1/\kappa)$, for ADF structures of square holes $a=\Lambda/3.75$ and gap separations $h_g=\Lambda/1000$, $\Lambda/100$, and $\Lambda/10$, respectively. In the three cases, the thickness of the plates is fixed at $h_m=\Lambda/1.875$. The shaded area highlights the area of negative $\mathrm{Re}(1/\kappa)$.

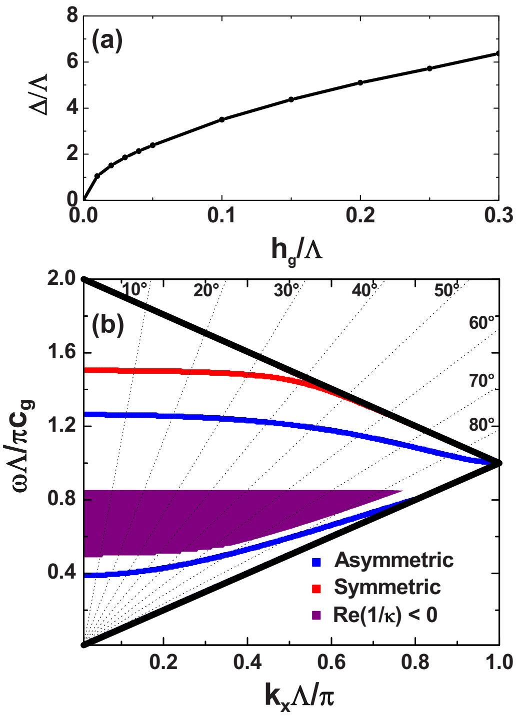

FIG. 4. (Color online) (a) Dependence of the wavelength width of the attenuation band, Δ, with the gap thickness, h_g, for normal incidence. (b) Dispersion with respect to the parallel momentum of the even and odd modes and the region of negative $\mathrm{Re}(1/\kappa)$. The geometrical parameters are: $a=\Lambda/3.75$, $h_m=\Lambda/1.875$, and $h_g=\Lambda/10$, as in Fig. 3(c). Dotted lines show the dispersion of incoming plane waves for different angles of incidence.

the use of an effective medium approach for describing an ADF metamaterial. From the practical point of view, this shows that an ADF structure can operate as a tunable acoustical device presenting a broadband, all angle blockage of sound. Importantly, the spectral location of this forbidden band and its linewidth can be engineered by changing the period of the hole array and the thickness of the gap layer placed between the two holey plates.

This work was financially supported by the Spanish Ministry of Science and Innovation under Project Nos. MAT2008-06609-C02 and CSD2007-046-NanoLight.es. J.C. gratefully acknowledges financial support from the Carlsberg Foundation under QUANTONICS Contract No. 2009-01-0167.

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